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FUEL CELLS

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FUEL CELLS

by

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1. Definition of the term "Fuel Cell".

A fuel cell can be defined as an electrochemical device in which the chemical energy of the reaction of a conventional fuel and air is converted directly into electrical energy. The fuel and air are supplied continuously to the cells through pipes, and the reaction products must also be removed continuously. The essential difference between fuel cells and heat engines is that in the former case the chemical energy is converted directly into electricity, without having first to be converted into heat energy; thus fuel cells are not subject to the limitations of the Carnot cycle, and they therefore hold out the prospect of a higher overall efficiency of conversion.

2. Advantages of fuel cells, compared with more conventional sources of electrical energy.

(a) The fundamental advantage of fuel cells is that, as mentioned above, they are not subject to the limitations of the Carnot cycle. The theoretical efficiency of the hydrogen/oxygen fuel cell at atmospheric temperature and pressure is about 83 per cent, and practical efficiencies of 50 to 70 per cent have been demonstrated under working conditions, the higher efficiencies in this case being obtained at low loads. In many applications, for example, the propulsion of vehicles, the fact that the highest efficiency is achieved under conditions of light load could be a very real advantage, because vehicles, both road and rail, are operated on relatively light loads for a large proportion of the time.

(b) Another important advantage which fuel cells, in common with many other types of battery, possess, is the ability to take large overloads for short periods of time; this is particularly valuable for traction applications, where rapid acceleration from rest is often of great importance; and a nigh starting torque for farm tractors and earth moving equipment of all kinds is sometimes vital, clutch and gearbox both being eliminated.

(c) Other advantages, which may or may not be important, depending on the application, are complete silence and lack of vibration, the fact that there are virtually no moving parts, and the fact that very complete combustion of the fuel should be attained, leading to lack of noxious exhaust fumes and smoke. Also, it should be possible to make the hydrogen/oxygen cell completely reversible, with further development. [1]

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[1] Bacon, F.T. Energy Storage based on Electrolysers and Hydrogen/Oxygen Fuel Cells. United Nations Conference on New Sources of Energy. Paper No. E/CONF. 35/GEN/9 (1961).

3. Basic reasons why fuel cells are not yet available for commercial purposes.

(a) The basic reasons in the past, and to a certain extent even now, for lack of reliability of fuel cells over long periods, are associated with corrosion of internal parts, in the presence of a strong electrolyte and oxygen, the gradual loss of catalytic activity of the electrode surfaces, the gradual flooding-up of wet-proofed carbon electrodes under certain conditions, leading to a loss in activity with time, and the slow creepage of molten electrolytes where these cannot be fully contained. All these problems are being worked on, and a number of ingenious solutions have already come to light.

(b) Another basic reason why fuel cells have not yet been adopted for general use is the fact that, so far as the author is aware, no complete working cell has yet been demonstrated which will operate really effectively on a commercially available hydrocarbon fuel, and air. Lastly, there is the difficulty of high capital cost; nearly all new devices suffer from this disadvantage, and it is only possible to overcome it when radically new production techniques have been worked out in practice.

4. Types of Cell which could be considered for use in the less developed areas of the world.

(a) It is convenient to classify the types of fuel cell proposed so far, into those working at atmospheric temperature up to say 100°C, those working at a medium temperature, around 200°C, and those working at a high temperature, say 550°C and upwards, with electrolytes of fused salts. It would seem probable that for ordinary commercial purposes, low temperature cells are likely to be used in small units, up to say 10 kW or rather more, in which rejection of waste heat is not likely to be a serious problem; medium temperature cells may be used in rather larger sizes, where it will no doubt be important to have as high a performance as possible so as to keep the capital cost down, rejection of waste heat, even with a high ambient temperature, being quite easy; whereas high temperature cells may be best suited for comparatively large scale generation of power, where the time taken to heat up from cold would be of relatively minor importance.

(b) Many types of low temperature cell have been tried and new types are constantly being described in the literature (it is impossible to list them in this short paper, but see Refs. [2] and [3]). Most of these low temperature cells use hydrogen or hydrazine (N_2H_4) as fuel, though it has been shown that methanol will also react; it has also been shown that air may be used in place of pure oxygen without much drop in performance.

(c) The only medium temperature cell which has been described in any detail is the one with which the author has been associated over many years. This cell always suffered from the disadvantage that it worked under considerable pressure, because of the rather high vapour pressure of the

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[2] Young, G.J. Fuel Cells. Reinhold Publishing Corporation, New York. (1960).

[3] Fuel Cells, Power for the Future. Fuel Cell Research Associates, Cambridge 38, Mass., U.S.A. (1960).

electrolyte, and this made it difficult to use air instead of oxygen, especially in small sizes, owing to the cost of compression; however, a modified version of the cell is being developed in the United States, initially for an important space project, and this cell will work at less than one atmosphere gauge pressure of oxygen; this should make it possible to use air, later on, for commercial applications. Hydrogen is the only fuel which has been shown to be effective in this type of cell.

(d) Lastly, high temperature cells using electrolytes of fused salts, usually carbonates, are being worked on by many different organisations. These cells, which operate at 500-700°C, have the great advantage that they will consume impure industrial gases, or vapourized hydrocarbons such as kerosene, and air. So far, it has not been possible to maintain a very high performance over a long period, and there are still some practical difficulties to be overcome; so the basic research work is still being done on small size single cells of relatively low power.

5. Types of fuel which can be considered for use in fuel cells.

(a) Almost all fossil fuels could be considered for operating fuel cells, but it must be clearly understood that most would require treatment of some sort before being fed into the cells. For example, liquid hydrocarbon fuels would have to be refined and gasified, although it must be conceded that certain workers have shown that liquid methanol will react when mixed with an electrolyte, though the reaction probably does not go to completion. Also, it has been shown that the rather special fuel, hydrazine, will react very well when mixed with the electrolyte; and cracked ammonia is also an attractive fuel for small units.

(b) As far as the author is aware, nobody has yet shown that a complete fuel cell will operate really successfully at a low, or even a medium temperature, on a hydrocarbon fuel (methanol is excepted, and is not strictly speaking a hydrocarbon in any case), though some success has been recorded with a fuel electrode alone. Even with high temperature cells, the trend now seems to be to react a hydrocarbon, such as natural gas, propane or butane, with steam in an external reformer, so that in fact the cell is fed with a mixture of hydrogen and carbon monoxide, both of which gases will react readily.

(c) As regards medium and low temperature cells suitable for commercial use, by far the most suitable fuel is hydrogen; it has been shown that carbon monoxide will also react at these temperatures, but the most promising cells, in the author's opinion, operate with an alkaline electrolyte, and all the carbon in the fuel will react to form carbonate. This in turn would mean the addition of a fairly large electrolyte regenerator, which is an added complication and which would be expensive to operate.

(d) The question then naturally arises as to whether a commercially available liquid hydrocarbon fuel, or natural gas (largely methane and ethane), or methanol could economically be converted, probably in a steam reformer, into relatively pure hydrogen, the latter gas being fed into the cells. Methanol would be the easiest fuel to treat in this way, but other less expensive fuels are liquefied petroleum gases (propane and butane), naphtha and on a larger scale even crude oil, besides natural gas which is in many areas the cheapest source of hydrogen that there is. The conversion

of various fuels into a form, suitable for use in a fuel cell, is discussed in Sections 7 and 8.

6. Effect of using air in place of oxygen.

(a) It can be said in principle that all types of fuel cell could be made to work on air instead of pure oxygen, though a great deal of the early work on medium and low temperature cells has in fact been done with oxygen; high temperature cells are normally operated on air without any difficulty. The main disadvantage associated with the use of air is a lowering in cell performance, due to the lower oxygen partial pressure; precise figures cannot be quoted at present. The other difficulty is associated with the gradual carbonation of alkaline electrolytes from the CO_2 content of the air, though this may not be as rapid as might be feared. Considerable experience is now being obtained in fuel cells using air, and the results have been distinctly encouraging; it has been found possible to consume quite a large fraction of the oxygen in the air, without a perceptible loss in performance.

(b) Without going into any detail it can be said that the use of air instead of oxygen is bound to raise certain difficulties, but these are by no means insuperable. It is realized of course that fuel cells must be made to operate on air before most commercial applications can be contemplated.

7. Efficiency of gas production, using liquid fuels; efficiency of fuel cells; and overall efficiency expected from complete plant.

(a) It has perhaps not been sufficiently realized in the past that the plant for producing a gaseous fuel acceptable to a fuel cell, from a commercially available and easily transportable liquid fuel, is of equal importance to the fuel cell itself. It is also important to view the plant as a whole, and perhaps to integrate it, so that for example waste heat from the fuel cell can be used effectively in the gas producer. It is only by careful design and forethought that the overall efficiency of the whole plant will exceed that of the best heat engine. One other important point is that in the past most gas production plants, especially for relatively pure hydrogen, have been of large size, and small plants have not been fully developed yet. The subject is a very large one and it is only possible to touch on one or two aspects of it in this paper.

(b) There seems little doubt that for small scale applications, using low or medium temperature fuel cells, the methanol-steam reaction has many advantages; the carbon dioxide in the gas produced is usually absorbed in monoethanolamine (MEA) solution. The purity of the hydrogen produced in this process is rather over 98 per cent, which should probably be acceptable for most types of fuel cell; and the process can be carried out at pressures up to 20 atmospheres or even more, if desired. Alternatively, the separation of the hydrogen from the CO_2 etc. can be done in a hydrogen diffusion cell, in which the hydrogen content of the gas mixture diffuses through the walls of small bore palladium alloy tubes, at 300-400°C and with a pressure difference of up to 27 atmospheres, thus securing a gas purity of practically 100 per cent; these diffusion cells have only been developed during the last few years, and would appear to be extremely promising for use in conjunction with fuel cells, if they can be made cheaply enough.

(c) In cases where methanol is too expensive, liquefied petroleum gases, naphtha, or even heavy fuel oil could be used; but with these fuels, the

gas from the reformer which operates at about 800°C, is largely hydrogen and carbon monoxide, and as the latter gas presents certain difficulties in low and medium temperature cells, one or even two stages of water-gas shift at about 400°C would be required, followed in each case by removal of the carbon dioxide. This, together with the probable necessity of feed desulphurisation, with naphtha or fuel oil, inevitably makes the plant more complex, and thus makes it likely that these fuels could only be economic in rather large plants. In this respect, high temperature cells possess a great advantage in that both hydrogen and carbon monoxide can be consumed electrochemically, and moreover they are quite unaffected by sulphur and other gaseous impurities, thus, a simple steam reformer is all that would be required, and some waste heat from the cell can contribute to the reforming reaction.

(d) The cheapest source of hydrogen is generally natural gas, which can be converted into hydrogen either by steam reforming or else by partial oxidation; with a large plant, producing enough gas to generate 35 MW in a fuel cell, the overall cost of hydrogen produced by the latter process has been stated to be as low as 0.34 penny/kWh produced in the cells; with smaller plants, the cost at present is much more than this, and may be perhaps 1.5 penny/kWh for a plant generating 1.4 MW.

(e) As regards thermal efficiency of hydrogen production, using say steam reforming of naphtha, it is believed that at the present time this will be 60-65 per cent for a plant supplying a 120 kW fuel cell, and about 49 per cent for a 3 kW unit; this includes purification with a palladium diffuser; efficiencies are rather lower than this with other methods of purification. However, it is believed that the efficiency of even the smaller unit could be brought up to 60-70 per cent with further development. Larger reformers have an efficiency of 80-85 per cent.

(f) With regard to the thermal efficiency of fuel cells, it is important to distinguish between free energy efficiency, and the efficiency based on the total heat of the reaction; when making comparisons with heat engines, it is necessary to take the latter figure, which, for hydrogen/oxygen cells, is substantially lower than the former. In the case of heat engines, the higher calorific value of the fuel should be taken, for a fair comparison. If the hydrogen/oxygen cell can operate at 1.0 V, the efficiency, based on the total heat, will be about 67 per cent; at 0.9 V it will be 60 per cent, and at 0.8 V it will be 54 per cent. As development proceeds, the working voltage is gradually being raised, and it is thought that it would now be fair to take a figure of 1.0 V at a reasonably high current density.

(g) Taking the two most optimistic efficiencies, namely 70 per cent for a small gas producer and 67 per cent for the fuel cell, the overall efficiency would be about 47 per cent; no allowance has been made for the possible integration of gas producer and fuel cell, and this would have to be worked out in detail before any figures could be quoted. And in a larger installation, with a reformer efficiency of say 80 per cent the overall efficiency would be 54 per cent. Using a high temperature cell it is believed that the efficiency of gas production could be in the region of 85 per cent; even if the efficiency of this type of cell is only 60 per cent, the overall efficiency would be 51 per cent.

8. Estimates of capital cost of gas production plant and fuel cells.

(a) It is thought that the best basis for an estimate of capital cost of gas production plant is pounds sterling per kW output from the fuel cell, assuming that 17 standard cubic feet per hour of hydrogen will produce 1 kW; this consumption rate may be improved somewhat, if cell efficiencies continue to rise. The capital cost varies greatly with the scale of the plant, large units being far cheaper per kW than small ones; it also varies according to the nature of the feedstock, the purity of gas required and the pressure.

(b) It has unfortunately been impossible to obtain costs for small gas producers, as these have not been fully developed yet; at present, it appears that the cost would be excessive for any commercial application. For a medium sized steam reforming plant of 1.2 MW, the cost might be £65-£77/kW for a plant generating 97% purity hydrogen (remainder CH_4) from fuel oil; for a plant of 2.5 MW, the cost would be £49-£55/kW; an American cost as low as £40/kW has been quoted for the latter size. If on the other hand impure hydrogen can be tolerated, a recently developed European process using liquefied petroleum gases and a top temperature of only about 600°C shows a cost as low as £16/kW; this process is a combination of partial oxidation and steam reforming and refers to a plant of 16 MW. There is great activity at the present time in the development of new processes for manufacturing hydrogen, and it is believed that the capital cost will continue to fall. If the hydrogen can be separated from impurities in a palladium alloy diffuser, the whole plant would be greatly simplified; but as this process is relatively new, the manufacturers prefer not to quote definite figures for capital cost at present.

(c) The capital cost of fuel cells is very difficult to assess at the present time, as none have so far been manufactured for sale, as far as is known. However, it is believed that a cost of £50/kW should be achieved for units of say 100 kW, in the present state of knowledge, for the medium temperature cell with which the author has been associated; this figure must be regarded as very tentative, as very few data are available for operation of this type of cell at low pressures, and the effect of using air instead of oxygen has not been properly assessed yet. Much lower costs have in fact been quoted in certain publications [3], and this tends to show that fuel cells are not inherently expensive; for example, a figure of £29/kW is quoted for a low temperature cell, assuming large production: another independent estimate gave only £14/kW for the medium temperature medium pressure cell, when used on a large scale.

(d) The above capital costs can be briefly summarised as follows, average prices being taken for the gas producers:-

	1.2 MW	2.5 MW	16 MW
Cost of gas producer	£71/kW	£52/kW	£16/kW
Cost of low temperature fuel cell	£29/kW	£29/kW	-
Cost of medium temperature fuel cell	£50/kW	£50/kW	-
Cost of high temperature fuel cell	-	--	£82 [3]
Total cost for low temperature fuel cell	£100/kW	£81/kW	-
Total cost for medium temperature fuel cell	£121/kW	£102/kW	-
Total cost for high temperature fuel cell	-	-	£98/kW

[3] See [3] on p. 2.

(e) If the figure of £14/kW can finally be achieved for the medium temperature cell, the total cost for a 2.5 MW unit would fall to £67/kW. Lastly, if a D.C./A.C. inverter is required, the cost would be between £10 and £15/kW [1], and this should be added to the above figures; if the solid state type of inverter can be used, the cost would be much less. It will be realised that these figures are very tentative, but are perhaps better than nothing; the main reason for quoting them at all is to show the importance of the cost of the gas producer.

9. Applications for which fuel cells may be particularly suited.

(a) It is probably true to say that, apart from special applications such as in space vehicles or in submarines, fuel cells are most likely to be used first in applications where for some reason the fuel used is relatively expensive, as in remote areas; and also in cases where direct current is required, for example as an alternative to diesel-electric generators either for railway traction or ship propulsion; in both these cases, electric drive has special advantages, and direct current is preferred.

(b) It is too difficult at present to express an opinion about the large scale production of power for electric supply in fuel cells, but in the less developed countries where there is no electricity grid, and where the size of units required is fairly small, the chances of competing with conventional generators would be much better, especially where natural gas is available; moreover, the large overload capacity could be of great value in dealing with peak loads of short duration. Large amounts of natural gas are still being wasted in certain oilfields; this could either be used for electricity generation in fuel cells in the surrounding areas, the gas being distributed in pipelines, or liquefied for oversea transport; or alternatively it could be converted into methanol, distributed in tankers or pipes, and used in small fuel cell power stations. It is conceivable that electrochemical industries could be set up in areas where very cheap natural gas is available, the low voltage direct current produced being led straight to the electrochemical cells with no need for rectifiers and transformers.

(c) Some interesting comparative figures for costs of small scale electrical transmission and diesel-generation are given in a recent paper by E.W. Golding on "Power from local energy resources" [4]. The capital cost of diesel generating sets varies, but a representative figure for a plant of several hundred kilowatts capacity is said to be £50/kW.

(d) When a really practical cell is produced which will consume raw hydrocarbons, or alternatively hydrogen containing a large percentage of impurities, the range of application will be vastly increased. And if a cell is finally developed which will consume say propane, and air, at a low temperature, the propulsion of heavy road vehicles and earth moving equipment might become a practical proposition.

(e) Apart from the initial difficulty of high capital cost, it is essential to demonstrate reliability over thousands of hours; the space programme should provide the answer to this very soon. Lastly, it will be

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[1] See [1] note on p. 1.

[4] Golding, E.W. Power from Local Energy Resources. United Nations Conference on New Sources of Energy. Paper No.E/CONF. 35/GEN/5 (1961)

necessary to build a number of complete plants, including gas production from a commercial fuel, and automatic controls to take care of varying loads, temperature control, removal of reaction products, besides control of start-up and shut-down procedure etc.; this will cost money, but it will undoubtedly be carried out by various organisations during the next few years.

10. Conclusions

(a) It seems almost certain now that a really dependable fuel cell of some kind will be produced during the next few years. But before fuel cells can compete on level terms with heat engines, it will be necessary to reduce the capital cost of the whole plant; it should be possible to achieve this, with respect to low and medium temperature cells, either by adopting a radically different method of hydrogen purification, for example in a palladium alloy diffuser, or else by developing a selective hydrogen electrode which will use the hydrogen content of the gas and reject the rest; and with respect to high temperature cells, by improving the performance by a sufficient amount to bring the capital cost of the cell itself down considerably. It is believed that the overall efficiency of the whole plant, including gas production, is already at an acceptable level, even with quite small plants.

(b) If a practical low or medium temperature hydrocarbon/air cell is in fact evolved, the whole position would be altered; a methanol/air cell is probably nearer, but a practical system has not yet been achieved. Rapid strides are now being made in fuel cell technology in many different countries, and it seems almost certain that fuel cells will come into use for special purposes, such as space exploration, during the next few years, for special kinds of commercial application a few years later, followed by the ultimate goal of application for general purposes, competing on level terms with heat engines, within at the most ten years from now.

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